Event selection, muon track reconstruction and momentum spectrum analysis for muon charged current events

Patrick Berghaus
Kansas State University
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An overview is given for the methods and procedures used in the reconstruction of the muon spectrum in muon neutrino charged current interactions. The calculation of the fraction of prompt events to total in the sample is described. The result is 0.56±0.17(stat) ±0.05(sys).

Introduction

Muon charged current events can be identified relatively easily and thus provide an independent sample that can be used to estimate the expected number of observable tau neutrino interactions. In order to do this it is important to find the fraction of muon events from neutrinos produced in charm decays (prompt) as opposed to those from light meson decays (nonprompt). This can be achieved by fitting the momentum spectrum of the primary muons to a mixture of the expected spectra for both sources and leaving the ratio as a free parameter. In the following the extraction of muon charged current events and the calculation of the prompt fraction in the total sample will be described.

Event Selection and Track Reconstruction

Event Sample

The events used in this analysis is the sample of 511 events selected at Nagoya University for attempted location in the emulsion. 261 events have a located primary vertex and 203 have complete emulsion information. Vertices for the events not located in the emulsion have been reconstructed electronically using the E872 offline analysis code.

Track reconstruction

In order to identify muon CC interactions, a track reconstruction algorithm was used to find tracks in the downstream drift chambers and check for correlated hits in the muon ID walls. Because of high hit multiplicity in those systems, no information from the vector drift chambers or the scintillating fiber system was used in the fit. Instead, the bend angle of the track in the analysis magnet was calculated using only the track parameters downstream of the magnet and the vertex position itself. An estimate for the bend angle error is given in Appendix I.

DC track reconstruction

The drift chamber tracks were found by reconstructing lines in the x view and then looking for intersecting hits in the u and v views to get spatial tracks. The requirement for an x view line was to have at least one hit in one of the x planes of each of the three drift chamber or hits in both x planes of two drift chambers. A drift chamber track required three additional hits in the u and/or v views. If there no muon candidate track was found in the event, the search was extended to tracks with only two u or v hits. Only tracks with

a slope of less than 400 mrad with respect to the beam axis were allowed. Figs. 1 and 2 show the distribution of $\dfrac{c^2}{dof}$ for DC lines and tracks and the theoretical curves for different n. Both data distributions agree with the theoretical expectation at low values before background from hit ambiguities and random hit alignment starts to dominate. For both x lines and complete spatial tracks a cut of $\dfrac{c^2}{dof} < 5$ was used.
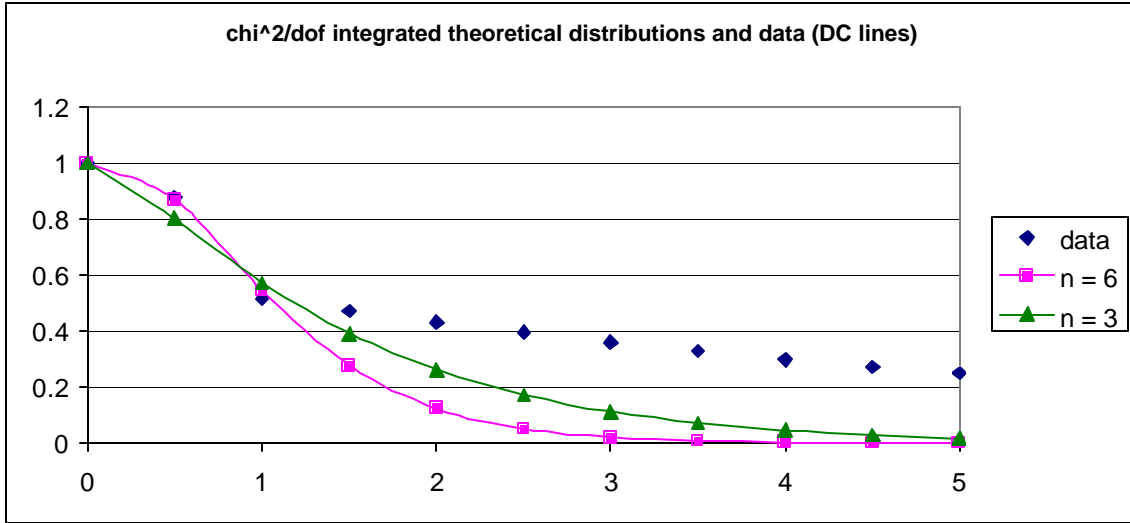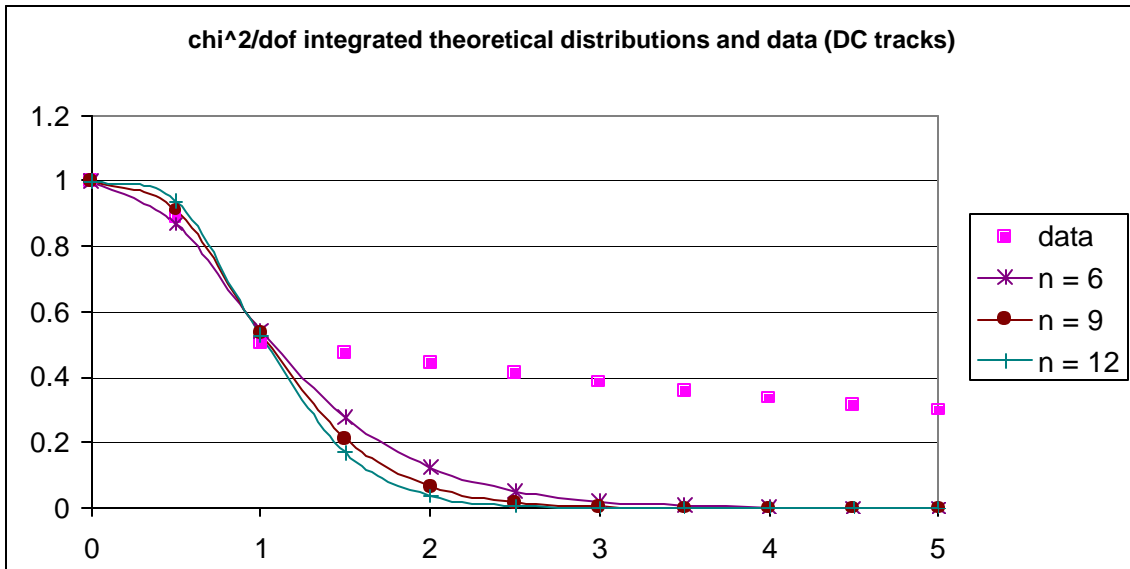

Figure 1

Figure 2

Muon identification

Drift chamber tracks were projected to the position of the muon ID walls and checked for adjacent hits within 10 cm of the track in the plane the track was projected on. A muon track was required to have 4 or more associated hits out of 6 possible, with at least one hit in each of the three muon ID walls. Figure 3 shows the distribution of hits per track in calibration (pw5) data. The fit was made assuming constant efficiencies for all tubes and planes, so the relative values for 4, 5 and 6 hits are:

$$f_6 = h^6$$
$$f_5 = 6h^5(1-h)$$
$$f_4 = 12h^4(1-h)^2$$

where f_n is the fraction of events for n muon ID hits and η is the efficiency of the muon tubes. The factor 12 (as opposed to 15 in the normal binomial distribution) in the last equation comes from the specific selection criterion requiring at least one hit in each wall.

The resulting value for the efficiency is 93%. Figure 4 shows the same distribution for neutrino events, which agrees with the calibration data within error bars.
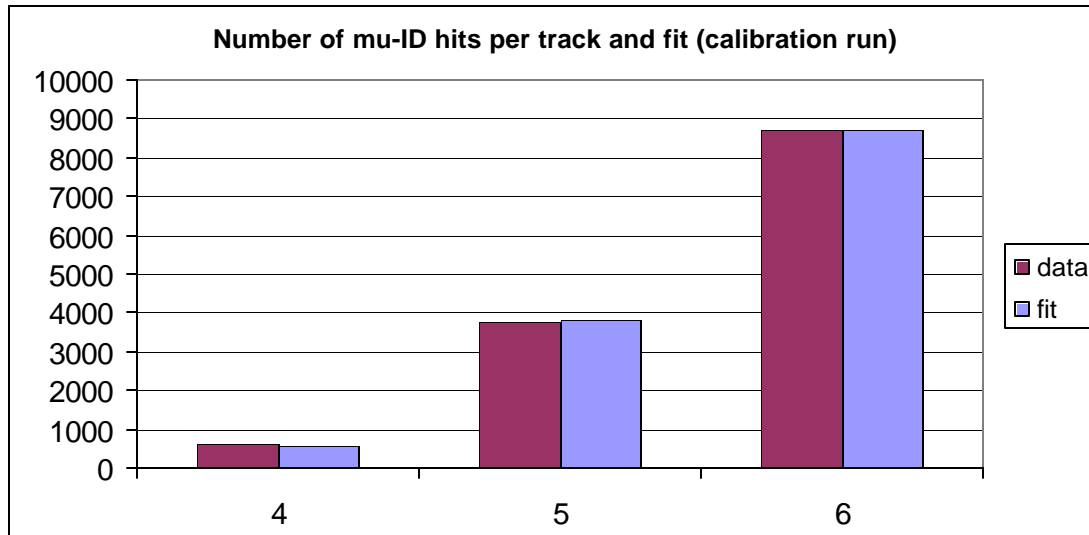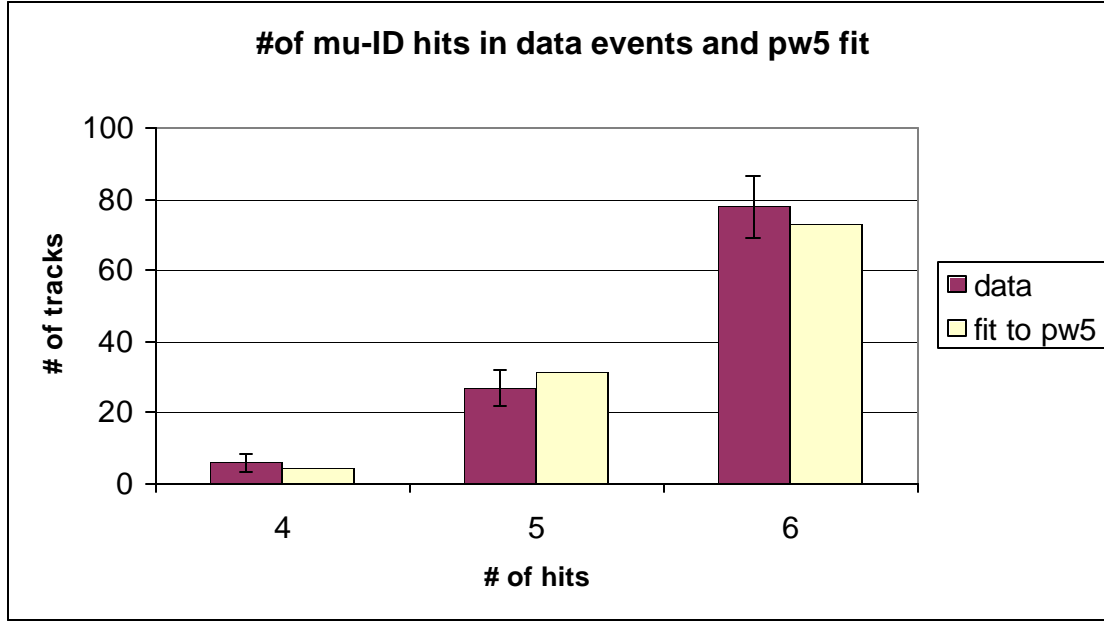

Figure 3

#of mu-ID hits in data events and pw5 fit

Figure 4

Electronic cuts

Once a muon candidate track was found, it was refit using all drift chamber and muon ID hits. Because of the high value of σ (8cm) for the muon walls, the final track was essentially the same as the original drift chamber track.

The following cuts were imposed on the final tracks in the offline analysis code:

-   $\dfrac{c^2}{dof} < 2$ (see Figs. 5, 6)
-   Distance cut requiring an impact parameter of < 2.5 cm at the vertex position in the y (non-bend) plane (see Figs. 7, 8)
-   Momentum >5GeV/c

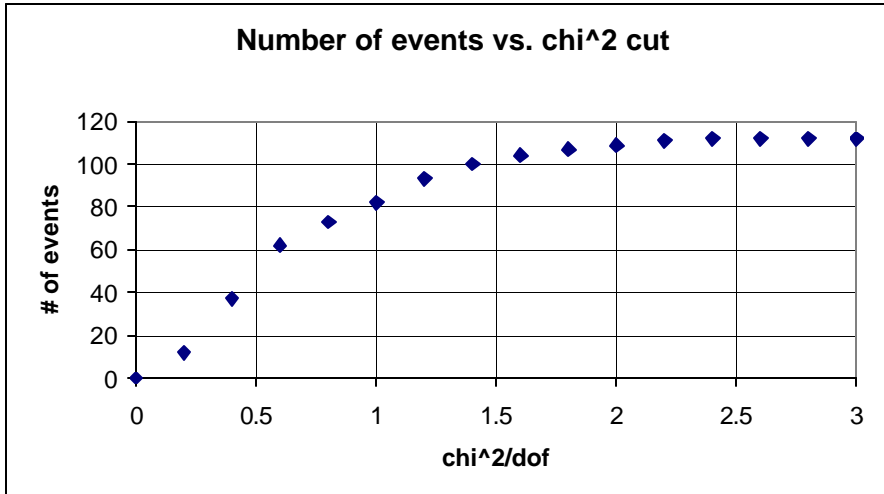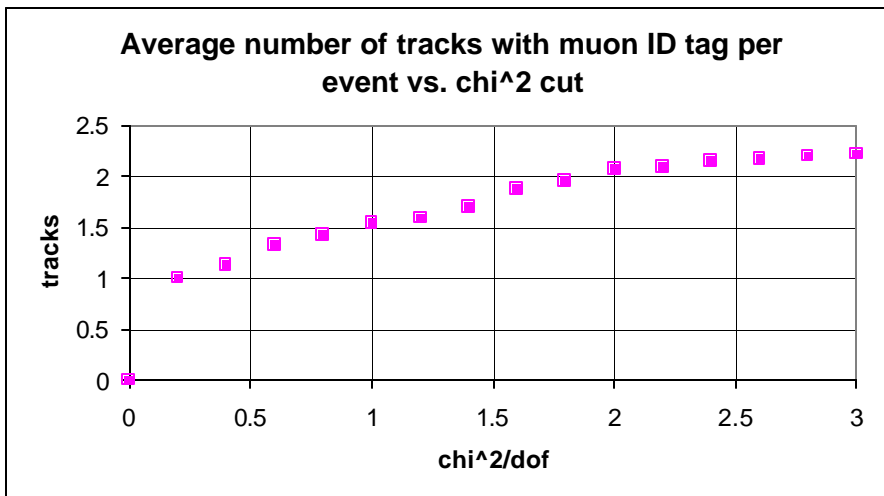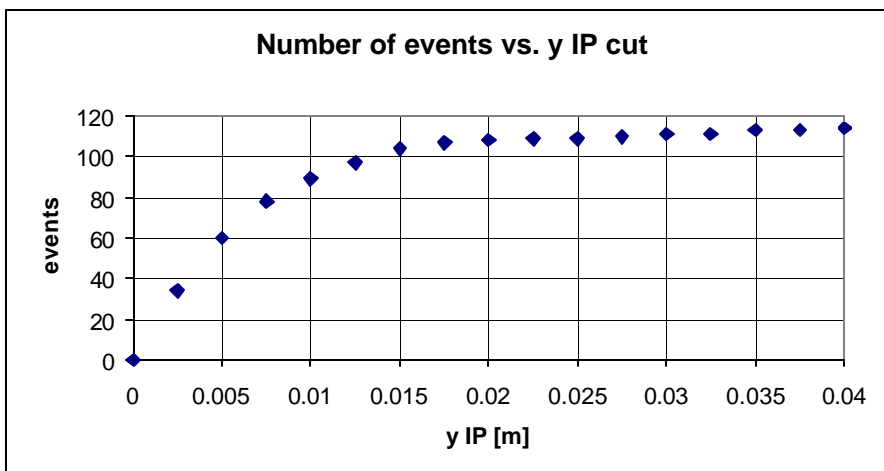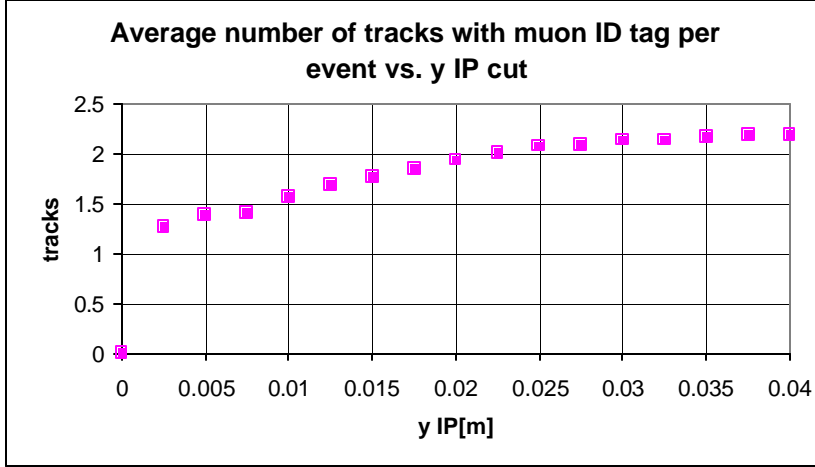**Figure 5**

Figure 6

Figure 7

Figure 8

Additional cuts

The remaining candidate tracks were visually scanned and possible background events were removed. The criteria for removal were:

- No latch hit or energy deposit in the lead glass calorimeter associated with the track
- Energy deposit but no latch hit and anomalous trigger timing ($\Delta t > 70ns$ between two trigger planes)
- Muon track pointing at calorimeter cluster with $> 5GeV$ energy deposit
- Multiple adjacent muon candidate tracks with irreconcilably different momentum values ($|\frac{1}{p_1} - \frac{1}{p_2}| > .02$)
- >3 DC tracks within 3 cm distance and >25 DC tracks within 20 cm.

The fitting routine allowed for a momentum cut as well. The final choice for the momentum cut and the reasoning behind it are described below. An overview of the effects of the different cuts is given in Appendix II.

Multiple tracks

In many cases there still remained several spatially clustered muon candidate tracks for each event (see multiplicity plots Figs. 6, 8). The final muon momentum was calculated using the average of the individual values weighted by the tracks' c^2 .

Monte Carlo simulation and momentum analysis

Monte Carlo

In the Monte Carlo simulation, muon charged current interactions were generated using LEPTO. Particles were tracked through the detector system with GEANT. Events were generated separately for neutrinos from charm meson (prompt) and π/K (nonprompt) decays so the ratio of the two components in the actual event sample could be used as the free parameter in a maximum likelihood fit to the data. The Monte Carlo muon momenta were smeared to account for the limited resolution of the spectrometer and multiple scattering effects in the material downstream of the magnet assuming Gaussian errors on the measured bend angle. The smearing was done with up to 3 times the error estimated in Appendix I without having a significant effect on the result. Figure 9 shows the normalized momentum spectra for both cases. In total, 50,000 muon CC Monte Carlo events were generated.
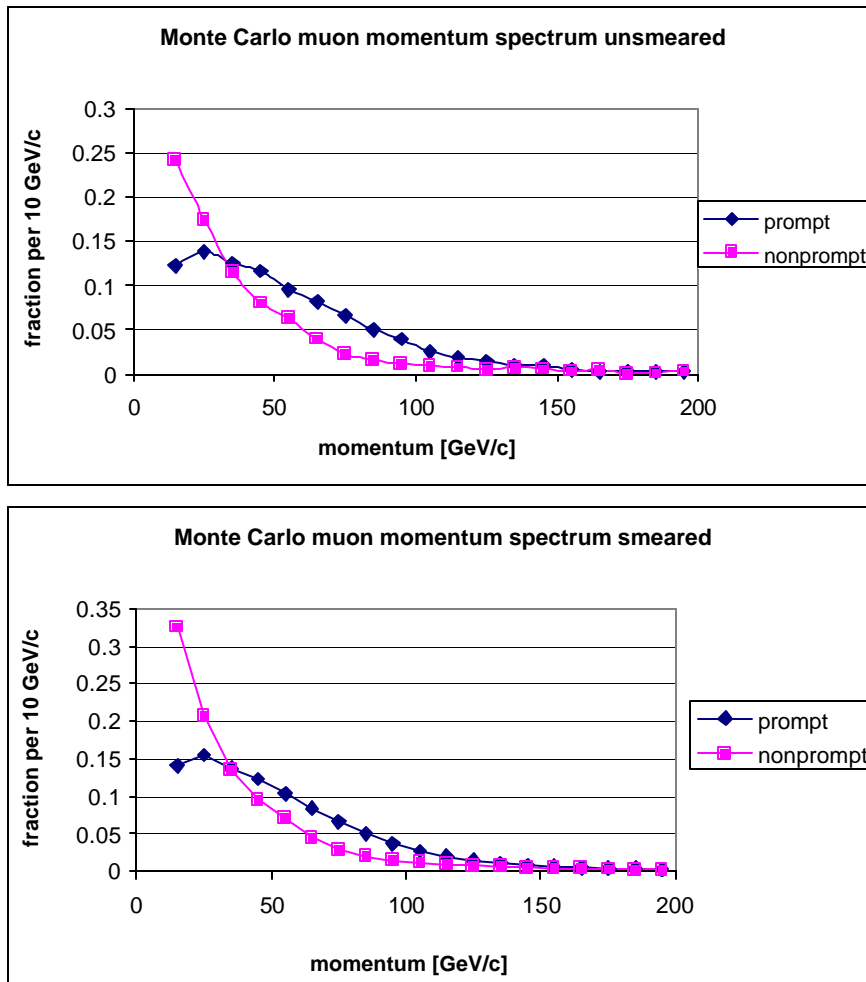

Figure 9

Cuts and weights

The simulated events were individually weighted to account for the biases of the actual event selection. This involved the following steps:

- Check on both trigger types and weight with relative number of protons on target during each of the triggers was used
- Use number of hits in first scintillator plane downstream of the vertex to model neutrino interaction candidate (cat3) selection
- Applying the same momentum and geometry cut on muon tracks as in track reconstruction
- For the located sample, there is another weight corresponding to the event location efficiency, which depends on the number of emulsion (primary charged) tracks.

Momentum analysis

The momentum spectrum of the muon data can be used to calculate the number of muon neutrinos produced in charm decays, and thus to obtain a normalization for the expected number of events of any interaction type.

Method

The muon spectrum obtained in the analysis was fit to a normalized combined Monte Carlo spectrum with the ratio of prompt to nonprompt events as the only free parameter. In order to check the consistency of the result the fit was done with several different momentum cuts and with samples that had more restrictive criteria for the number of muon ID hits (no tracks with 4 hits, only tracks with 6 hits).
Figure 10 shows the expected statistical fluctuations in the resulting value for the prompt/total fraction caused by variation of the momentum cut. It is based on 20 Monte Carlo event samples each with the same number of events as the data.
Figure 11 shows the variation of the result for the three different samples (6,6+5,6+5+4 muon ID hits) with varying momentum cuts. The error bars indicate the expected fluctuations of the result due to reduced statistics with respect to the value for the largest sample.
Figure 12 shows the variation of the value for all events in dependence of the momentum cut. The error bars indicate the expected fluctuations with respect to the value calculated with a 10 GeV/c momentum cut due to reduction of statistics and loss of discriminating power when a smaller fraction of the total spectrum is used for the fit.
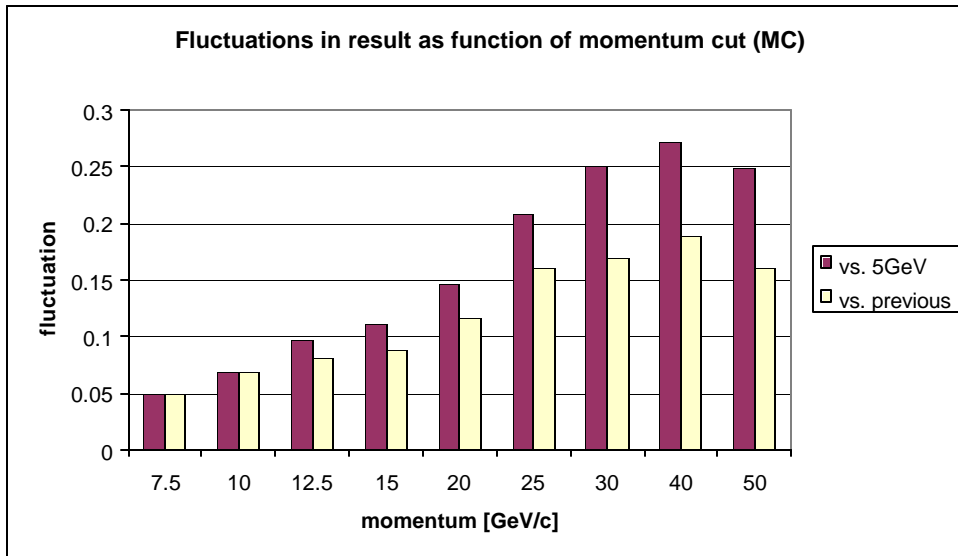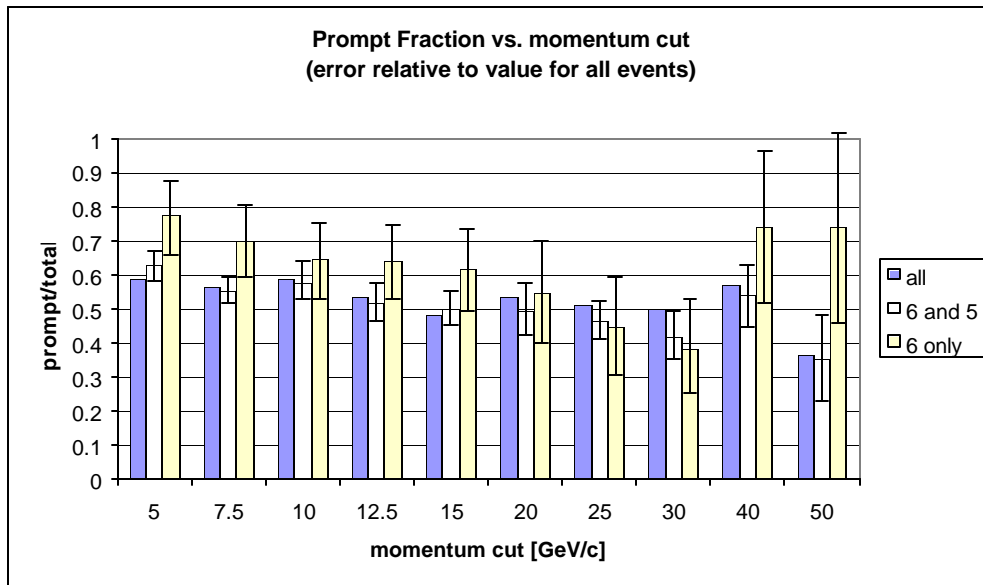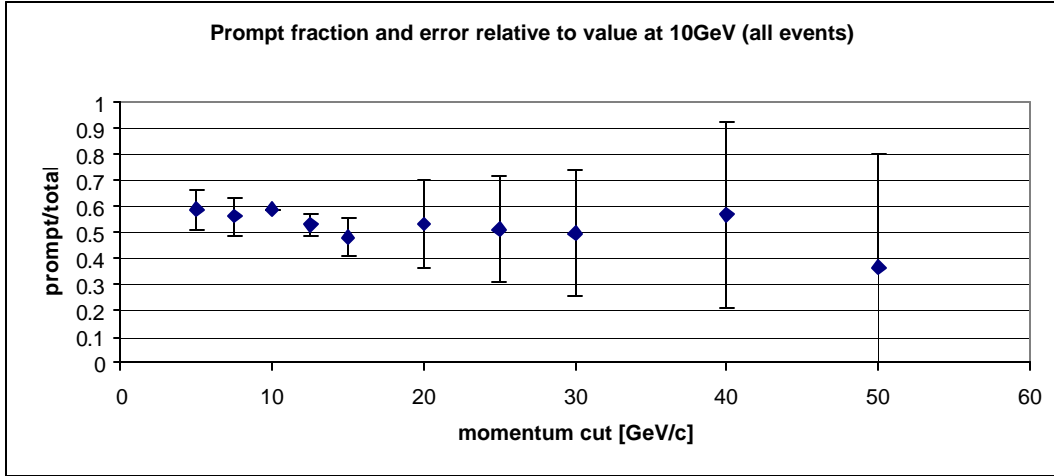
Figure10

Figure 11

Figure 12

Result

From Figure 11 it can be seen that the values for different event samples are not consistent within error bars below 10 GeV, indicating some kind of poorly understood background source at low energies. Above that value there is no statistically significant discrepancy between the values for the different samples. Figure 12 shows that the value using all events is reasonably consistent for a wide range of momentum cuts. Taking these facts into account the final result was calculated using a momentum cut of 10 GeV. Figure 13 shows the individual contribution and their sum, representing the final fit.

The value for the fraction of prompt over total muon events from this fit is $0.56\pm0.17(\text{stat}) \pm0.05(\text{sys.})$, where the systematic error was estimated by using different methods of binning the data and smearing the momentum.
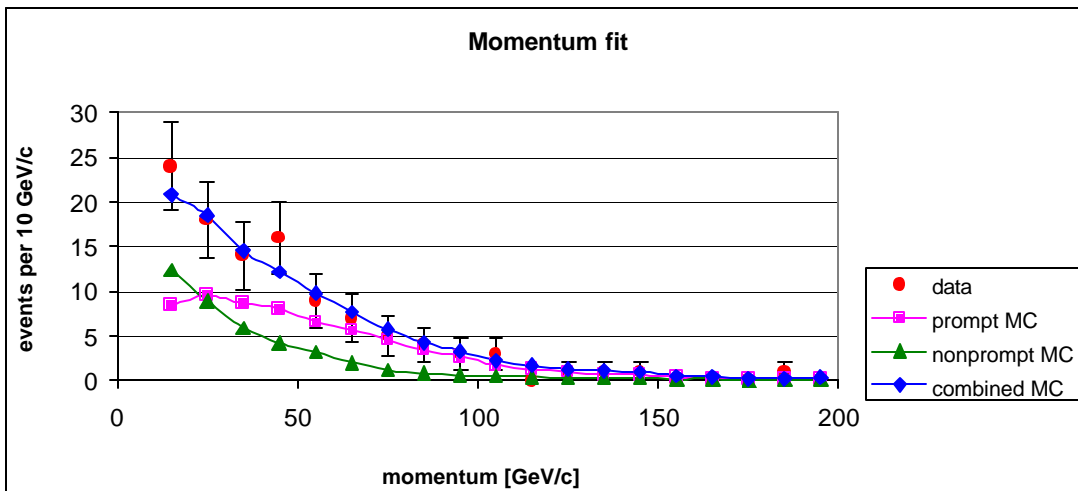

Figure 13

Appendices

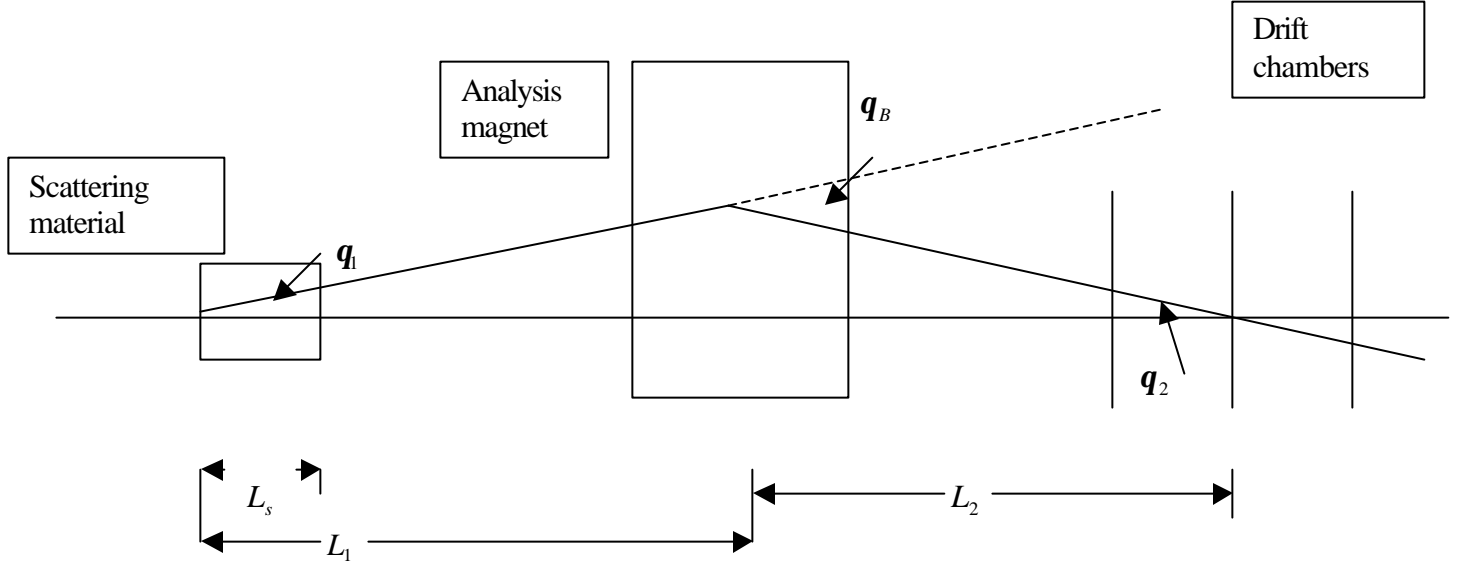## I. Measurement and multiple scattering error estimate

Figure 14

The two main contributions to the measurement error are multiple scattering in the emulsion modules and the measurement error of the downstream drift chambers. Figure 13 shows a sketch of the apparatus with all relevant quantities. The equations for the error on the measured bend angle from these two contributions are:

$$MS : d\boldsymbol{q}_{B,MS} = (1 - \frac{1}{\sqrt{3}}) \frac{L_S}{L_1} \boldsymbol{q}_{MS}$$

and

$$DC : d\boldsymbol{q}_{B,DC} = d\boldsymbol{q}_2 + \frac{d\boldsymbol{q}_2 L_2}{L_1}$$

with

$\boldsymbol{q}_{MS}$: multiple scattering angle

$d\boldsymbol{q}_2$: angular DC error

The total error on the bend angle is therefore:

$$(dq_B)^2 = ((1 - \frac{1}{\sqrt{3}}) \frac{L_S}{L_1} \frac{.015 GeV}{p} \sqrt{\frac{X}{X_0}})^2 + (dq_2(1 + \frac{L_2}{L_1}))^2$$

To obtain an upper bound for the error, the following values were used:

$\sqrt{\dfrac{X}{X_0}}$	10
dq_2	0.3 mrad
L_1	3 m
L_2	3 m
L_s	1 m

Table 1: Values used for estimate of bend angle error

This leads to an error on the bend angle of:

$$dq_B = \sqrt{((1 - \frac{1}{\sqrt{3}}) \frac{1}{3} \frac{0.015 GeV}{p} 10)^2 + (0.3 mrad \cdot 2)^2} = \sqrt{(\frac{0.021 GeV}{p})^2 + 0.6^2} \, mrad$$

II. Cuts used in the event selection

Cut	Events removed	Remaining events
Original Sample from offline analysis code		**134**
10 GeV cut	9	125
No EMCal energy or latch	2	123
No EMCal latch, bad timing	7	116
EMCal cluster > 5 GeV	1	115
Irreconcilable momentum values	1	114
Isolation cut	5	109
Final Sample used in fit		**109**

Table 2: Cuts and effects of cuts

The cuts are listed in the order they were applied. If an event failed two cuts it is only listed for the first.